MIDTERM 2

ECE 371 – Fall 2019

MATERIALS AND DEVICES

UNIVERSITY OF NEW MEXICO

Thursday October 31st, 2019

Time Limit: 1 hour 15 minutes

Exam is closed book and notes, 1 sheet of 8.5” x 11” notes allowed

Calculators okay, no phones!

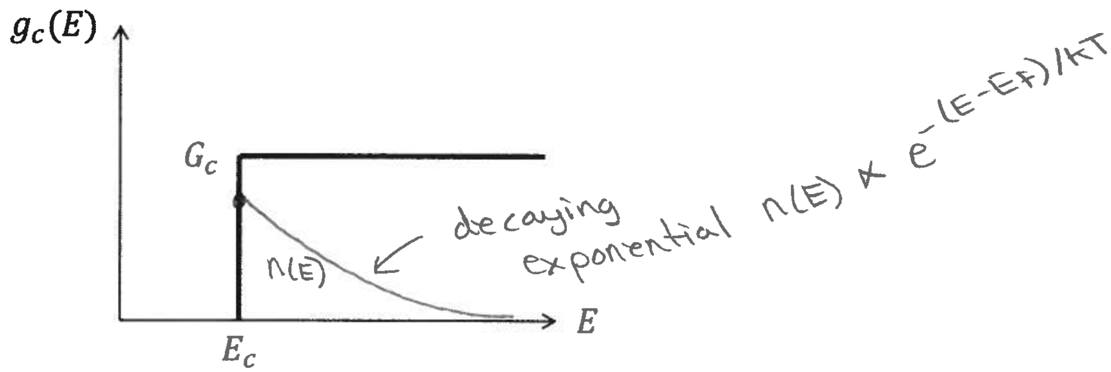
(100 points, 20% of course grade)

NOTE: Point totals for problems in the solutions are from older exams and not the same as those used this year. Please refer to your exam for the correct point totals used for each problem this year.

Name: ________________________________ Score:____________

(25 points)

1. Consider a semiconductor with a conduction band density of states $g_c(E) = G_c$, where G_c is a constant for $E \geq E_c$ and 0 for $E < E_c$ as shown in the plot below.



(a) Determine an expression for the total number of *energy states per volume* (#/cm³) between E_c and $E_c + 3kT$.

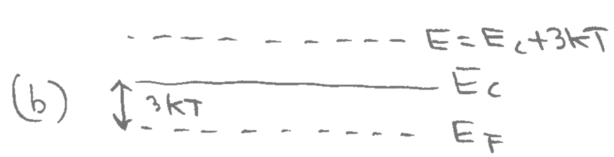
(b) If the Fermi level is $3kT$ below E_c, what is the probability of occupation for a state at an energy $E_c + 3kT$?

(c) Is the Boltzmann approximation valid for the calculation in part (b)? Why or why not? Justify your answer numerically.

(d) On the plot above, sketch the electron concentration $n(E)$ as a function of energy for this material and indicate its functional dependence on energy (e.g., constant, decaying exponential, increasing exponential, square root, etc.)

(a) $$\frac{\#}{cm^3} = \int_{E_c}^{E_c+3kT} g_c(E)\, dE = \int_{E_c}^{E_c+3kT} G_c\, dE = G_c E \Big|_{E_c}^{E_c+3kT} = \boxed{G_c 3kT}$$

(b)



$$F_F(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

$E_F = E_c - 3kT$

$$= \frac{1}{1 + e^{(E_c + 3kT - E_c + 3kT)/kT}} = \frac{1}{1 + e^{6}}$$

$$\boxed{= 0.60247}$$

(c) Boltzmann $\Rightarrow$ $f_F(E) \approx e^{-(E-E_F)/kT}$

$$= e^{-6} = 0.00248$$

Fermi Dirac $\Rightarrow$ $f_F(E) = 0.00247$ From part (b)

So, yes. Boltzmann is valid because they are very close

(d) See plot for electron concentration per energy $n(E)$

since $n(E) = \underbrace{g_c(E)}_{\text{constant}} \underbrace{f_F(E)}_{e^{-(E-E_F)/kT} \text{ under Boltzmann}} dE$ $\Rightarrow$ $n(E)$ will simply look like the Boltzmann distribution since D.O.S. is constant

$$n(E) \propto e^{-(E-E_F)/kT} \quad \text{for } E \geq E_c$$

(30 points)

2. Consider silicon at T = 300 K doped with 1e17 cm^{-3} boron atoms and 5e16 cm^{-3} phosphorus atoms. Assume 100% ionization.

(a) Write down an expression for the charge neutrality condition in a doped semiconductor.

(b) Determine the equilibrium electron (n_0) and hole (p_0) concentrations.

(c) Determine the location of the Fermi level (E_F) with respect to the valence band edge (E_v).

(d) If the temperature is increased, what will happen to the location of the Fermi level? You must justify your answer.

(i) It will stay the same
(ii) It will move higher in energy
(iii) It will move lower in energy

(a) $n_0 + N_a^- = p_0 + N_d^+$ in general

For 100% ionization

$$\boxed{n_0 + N_a = p_0 + N_d}$$

(b) Boron = group III → acceptor → $N_a = 1e17\ cm^{-3}$

Phosphorus = group V → donor → $N_d = 5e16\ cm^{-3}$

since $N_a > N_d \Rightarrow$ p-type

in general $p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}$

$\cong N_a - N_d$ since $N_a - N_d >> n_i$

so $p_0 = 1e17\ cm^{-3} - 5e16\ cm^{-3} = \boxed{5e16\ cm^{-3}}$

$n_0 = \frac{n_i^2}{p_0} = \frac{(1.5\times10^{10}\ cm^{-3})^2}{5e16\ cm^{-3}} = \boxed{4500\ cm^{-3}}$

(c) Find $E_F - E_V$

we know $P_o = N_V \exp\left[\frac{-(E_F - E_V)}{kT}\right]$

$N_{V_{Si}}$ @ 300K $= 1.04 \times 10^{19}\ cm^{-3}$

$$\ln\left(\frac{P_o}{N_V}\right) = \frac{-(E_F - E_V)}{kT}$$

$$-kT \ln\left(\frac{P_o}{N_V}\right) = E_F - E_V$$

so $E_F = E_V - kT\ln\left(\frac{P_o}{N_V}\right)$

$$E_F = E_V - (0.0259eV)\ln\left(\frac{5\times10^{16}\ cm^{-3}}{1.04\times10^{19}\ cm^{-3}}\right)$$

$$\boxed{E_F = E_V + 0.138\ eV}$$

(d) IF T ↑, then the intrinsic carrier concentration will go up from

$$n_i^2 = N_c N_V \exp\left(\frac{-E_g}{kT}\right)$$

⟹ the material will become "more intrinsic" and E_F will move closer to E_{F_i}

so $\boxed{E_F \text{ will move } \underline{\text{up}} \text{ in Energy}}$

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